

Gradient-index lens rod based probe for office-based optical coherence tomography of the human larynx

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Abstract. Optical coherence tomography (OCT) is an evolving noninvasive imaging modality that has been used to image the human larynx during surgical endoscopy. The design of a long gradient-index lens-based probe capable of capturing images of the human larynx by use of spectral domain OCT during a typical office-based laryngoscopy examination is presented. An optical-ballast-based 4f optical relay system is proposed to realize variable working distance with a constant optical delay. *In vivo* OCT imaging of the human larynx is demonstrated. Office-based OCT is a promising imaging modality for early laryngeal cancer diagnosis. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3076198]

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1 Introduction

Laryngeal carcinoma is one of the most common primary head and neck malignancies. Despite significant advances in cancer treatment, early detection of a malignant lesion and its curable precursors is paramount to ensure successful treatment and patient survival. Flexible fiber optic or rigid endoscopes are normally inserted through the nose or into the pharynx for conventional physical examinations, but it remains difficult to differentiate benign, premalignant, and malignant lesions, characterized by identical symptoms such as throat pain, coughing, or hoarseness, and nearly identical

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physical appearance. Both conventional examination and endoscopy lack the ability to visualize the depth of penetration of disease in deeper layers of tissue. Therefore, laryngeal cancer diagnosis has to rely on biopsies that require a general anesthesia and surgical endoscopy. This invasive procedure may have a detrimental effect on the patient's voice. Risks of a biopsy with surgical endoscopy may be considerable, since it is often difficult to obtain a representative biopsy from a suspicious malignant lesion, which sometimes may be missed due to sampling errors. Repeated biopsies are common to ascertain a definite diagnosis, and will bring even higher risks, regardless of the human toll exacted on patients and their families, costs associated with surgery, and patient time away from work.

Hence, there is a huge need to develop a fast, mobile, and noninvasive diagnostic technology for early detection and monitoring of laryngeal malignant lesions. Optical coherence tomography (OCT) is an evolving technology for performing high-resolution cross sectional micron scale imaging.¹ OCT performs imaging in biological tissues by directing an optical beam of infrared light onto the tissue and measuring the intensity and phase of the backscattered light from microstructures of the tissue at different depths. OCT can function as a powerful imaging technology for optical biopsy and has been used to image the larynx during surgical endoscopy.²⁻⁴ OCT imaging of the larynx in awake patients in an office setting has been limited, because several challenges exist including patient and physician movements and the position of the larynx deep within the neck. Recently we reported an office-based laryngeal time-domain OCT imaging device.⁵ A rigid laryngoscope serves as a platform to which a second device can be attached to perform simultaneous OCT imaging. However, the scanning mechanism was slow, thus it was very difficult to obtain OCT images due to movements of both the physician's hand and patient's larynx.

In this work, we demonstrate a second-generation office-based laryngeal OCT imaging device to address the difficulties we met in our previous study.⁵ We propose a novel gradient-index (GRIN)-lens-based probe capable of capturing images of the human larynx by use of spectral domain OCT. An optical relay system based on the principle of optical ballast⁶ is designed to fulfill constant-optical-delay dynamic focusing. *In-vivo* noninvasive and cross sectional imaging is possible during awake office-based laryngoscopy examination.

The importance of a tunable working distance was previously addressed⁵ and is briefly summarized as follows. In an OCT sampling arm, only the backscattered signal, of which the optical path length matches that of the reference arm, can be detected. In laryngeal endoscopy, the depth of the larynx in the throat and the path length light must travel from the incisors to the vocal cords vary markedly from patient to patient. Hence, a mechanism is required to allow active adjustment of the working distance. However, changing the optical path length of the reference arm to match a variable working distance is difficult for several reasons, the most important of which is that there is no means of knowing *a priori* whether the sampling beam is optimally focused on the specimen. Secondly, the depth of the larynx in the throat changes dynamically with patient posture and position. The most convenient solution is to maintain a constant optical delay in the sample

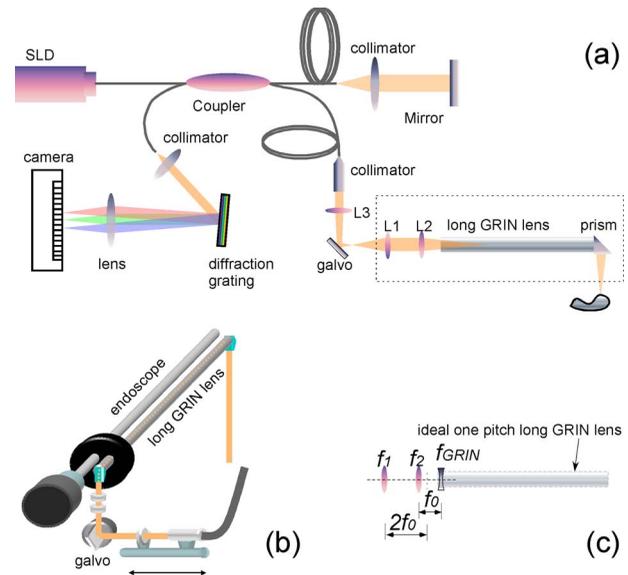


Fig. 1 (a) Schematic diagram of the long GRIN-lens-based laryngeal SDOCT imaging system. (b) 3-D design of laryngeal OCT probe, and (c) the formation of 4f optical relay system based on optical ballast.

arm during tuning of the working distance to ensure that the depth scanning range is always in focus, since the device must quickly adjust to image the larynx as it changes position within the pharynx. A depth adjustment function is essential for tracking the larynx.

Figure 1 shows the schematic diagram of the long GRIN-lens-based laryngeal spectral domain OCT (SDOCT) system. A 10-mW superluminescent diode (SLD) having a 1310-nm center wavelength with a full width at half maximum of 80 nm was coupled into the source arm of a fiber-based Michelson interferometer. Backreflected or backscattered light signals from different depths within tissue interfere with light from a reference path with a known delay in the detector arm. A spectrometer consisting of a diffraction grating (500 lines/mm) and a 1×1024 InGaAs detector array (SU1024-1.7T, Sensors Unlimited; Princeton, New Jersey) was used to detect the spectral interference signal to measure the echo time delay and magnitude of backreflected and backscattered light by Fourier transformation, and generate cross sectional images at 8 frames/s. The wavelength range on the array was 130 nm, corresponding to a spectral distribution of 0.13 nm/pixel and an imaging depth of 3.6 mm in air.

The sketch diagram of the probe design is shown in Figs. 1(b) and 1(c). The probe design should address a variable working distance with a constant optical delay. The one-pitch long GRIN (gradient index) lens (22 cm, Gradient Lens Corporation, Rochester, New York) used in this design can be considered as an optical relay for visible wavelength.^{7,8} The focal length of a long GRIN lens is given as

$$f_{GRIN} = \frac{1}{n_0 \sqrt{A} \sin L \sqrt{A}}, \quad (1)$$

where A is a constant for a particular lens for a particular wavelength, and L is the length of the GRIN lens. For an ideal one pitch, L is given as $2\pi/\sqrt{A}$ and the focal length f_{GRIN}

becomes infinite. Any light beam entering the GRIN lens rod will come out from the distal end of the lens with the same direction and same height (relative to the axis of the rod), thus an ideal one-pitch GRIN lens can be considered as an optical relay.

However, for the 1310-nm wavelength, which is the center wavelength of the OCT light source, the GRIN lens is close to one pitch but cannot be considered as an ideal optical relay anymore, especially when the average working distance of the probe (or the beam coming out of the probe tip) reaches about 65 mm for laryngeal imaging. However, the long GRIN lens (less than an ideal one pitch for 1310-nm wavelength) can be considered as a composite of an ideal one-pitch GRIN lens, which will be an ideal optical relay for IR light of 1310 nm, and a negative short GRIN (NS-GRIN) lens, of which the focal length is the same as that of the original long GRIN lens as

$$f_{\text{GRIN}} = [n_0 \sqrt{A_{\text{IR}}} \sin L \sqrt{A_{\text{IR}}}]^{-1},$$

where A_{IR} is now the lens constant for 1310-nm light.

To achieve an ideal optical relay, the GRIN lens is used with a group of lenses L_1 and L_2 to form a so-called optical ballast⁶ within a $4f$ optical system. Assume the focal lengths of the previous three lengths are labeled as f_{GRIN} , f_1 , and f_2 (with $f_1 = f_2 = f_0$), respectively. Figure 1(c) shows the sketch diagram of the probe design. If the distance between the two principal planes of the lens L_2 and NS-GRIN lens is equal to f_0 , i.e., the NS-GRIN lens is located at the rear focus of lens L_2 , the composite focal length of L_2 and the NS-GRIN lens will be

$$\frac{f_0 f_{\text{GRIN}}}{f_0 + f_{\text{GRIN}} - f_0} = f_0, \quad (2)$$

which shows the same focal power of the lens L_2 . Thus, the lens L_2 is named an optical ballast.⁶ If the distance between the two principal planes of L_1 and the composite lens (of the NS-GRIN lens and L_2) is adjusted to be $2f_0$, they will make up a $4f$ optical system with magnification of one and can be considered an optical relay.

The sample beam from the OCT system is collimated, passes through a focusing lens L_3 , and reflects 90 deg to the fixed lens group by a scanning galvo. The fiber and collimating and focusing lenses are fixed together so that they can be moved along the propagation direction. At the proximal tip of the GRIN lens, a 90-deg prism is attached to fold the light path [Fig. 1(b)]. At the distal tip of the GRIN lens, a customized prism is attached to reflect light 90 or 60 deg down to the larynx due to the anatomy of the patient. The device is coupled to the laryngoscope by a carriage. The endoscope and the OCT device are held together in a “double-barreled” configuration [Figs. 2(a) and 2(b)]. The collimator and lens L_3 are assembled onto a slider and can be moved back and forth together for working distance adjustment by the physician during the examination [Fig. 2(c)]. Since all fixed optics can be considered an optical relay, the optical delay of the focal point remains constant during adjustment of the working distance. During the examination, both the dual-channel endoscope and OCT signals are digitized and displayed on a single monitor.



Fig. 2 (a) OCT probe attached to the laryngoscope; (b) defogging before (c) insertion of the probe into pharynx for examination; and (d) dual-channel office-based OCT laryngeal probe in use during laryngeal examination.

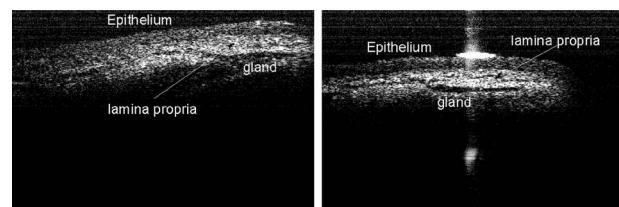
A flat quartz window together with its housing serves to shield the tube from fluids within the oral cavity and pharynx, and, since it can be sterilized, ensures that each patient is examined with a clean instrument. Defogging is important to prevent the coagulation of water vapor outside the shielding window. Otherwise, limited visibility will greatly degrade the acquired OCT image quality. For this purpose, a hair dryer is used to heat the probe up before insertion of the probe into the pharynx [Figs. 2(b) and 2(c)].

Since a GRIN lens rod and a prism are employed in the sampling arm, dispersion compensation is important to achieve high resolution. The dispersion can be measured with a mirror as a sample by constructing the complex representation of the spectral fringe pattern and correcting the phase as a function of the wave number.⁹ Thus, dispersion can be compensated by taking the product of the spectrum and the conjugate of the phase term of dispersion.

Normal subjects were evaluated under aegis of the Institutional Review Board at the University of California, Irvine. Video 1 shows an acquired movie of a human epiglottis captured with 8 frames per second. Video 1 clearly identifies the epithelium, lamina propria, and glands. The depth resolution of the image is $7 \mu\text{m}$ and the lateral resolution is $20 \mu\text{m}$. The imaging depth is 3.6 mm in air (2.6 mm in tissue). The lateral scanning range varies for different working distances and is about 5 mm when the working distance is 65 mm. The image is comparable with images obtained in anesthetized patients during surgical endoscopy.²

2 Discussion

Flexible and rigid endoscopes are two possible platforms that an OCT probe can be attached to. Previously we demonstrated



Video 1 OCT images from the epiglottis under examination of the office-based laryngeal probe. The epithelium, lamina propria and glands are clearly identified. (QuickTime, 9.9 MB). [URL: <http://dx.doi.org/10.1117/1.3076198.1>]

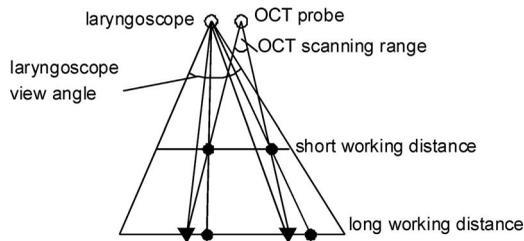


Fig. 3 The double-barreled configuration helps physicians to find the working distance. ▼ shows the OCT scanning range at a long working distance, while ● shows the OCT scanning range at a short working distance and its video projection onto the long working distance case.

a flexible probe that combined the OCT device and flexible endoscope.¹⁰ Comparing the two approaches, the flexible approach has the advantages of a fixed working distance (near-contact or contact), thus physicians can handle the device easier. However, due to the essentiality of the near-contact or contact measurement, physicians will run a little risk to touch the patient's vocal cords, despite that the vocal cords are under local anaesthesia. Also, fast scanning is difficult with the current device, which results in motion artifacts due to reflex of the vocal cords. The rigid approach demonstrated in this work can realize fast scanning (8 frames/s, even faster if a sweep-source-based OCT system is utilized), thus motion artifact is reduced. Since the device is cantilevered about 5 to 8 cm above the vocal cords, no anaesthesia and no risk is taken in this approach. However, since the working distance is different from patient to patient, physicians have to practice adjusting the working distance while holding the probe steady. There is a learning curve to the procedure of adjusting the working distance. Due to the double-barreled configuration, tissues with different working distance will have different OCT scanning ranges projecting onto the monitor of the conventional video, as shown is Fig. 3. This helps physicians to figure out the right working distance quickly. Another difference between the flexible and rigid approach is that they are only good at one view orientation—a side view for a flexible approach, or front view for a rigid approach, respectively.

The optical relay design is the key technique in this study. In our previous study,⁵ we already addressed the importance of continuing a constant optical delay while tuning the working distance, which ensures that the depth imaging range is always in focus. Two important ideas utilized in this work are emphasized as follows. 1. The long GRIN lens is located at the rear focus of lens L_2 , so that the focal length of the long GRIN lens does not affect the focal length of the composite lens group. 2. Positions of the scanning mirror and the proximal tip of the GRIN lens are satisfied with an object-image relationship for lenses L_1 and L_2 , thus the light beam will be kept within the aperture of the GRIN lens during lateral scanning.

Compared with our first generation one,⁵ the second-generation rigid probe demonstrate in this work overcomes the disadvantages of slow scanning, thus is much more convenient for physicians to manipulate the probe.

In summary, we demonstrate a novel long GRIN-lens-based OCT sampling device capable of capturing *in-vivo* images with 8 fps during a typical office-based laryngoscopy examination. Taking advantage of performance without the need for general anaesthesia or tissue removal, office-based OCT has potential to guide surgical biopsies, direct therapy, and monitor disease. This is a promising imaging modality to study the larynx.

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